Investigation of Defect Mode Properties for Defective Gallium Arsenide Based One Dimensional Photonic Crystal

Arvind Sharma

Associate Professor, Department of Physics, Govt. Dungar College, Bikaner, Rajasthan, India

---***---

Abstract- In the present work, we have theoretically proposed a Gallium arsenide based defective one dimensional photonic crystal. The transfer matrix method (TMM) is used to analyses the transmittance spectra. The device is designed as multilayer structure ($GaAs/BaF_2$) structure with defect in the middle of the periodic photonic crystal system. In this system the Gallium arsenide as high refractive index material and barium fluoride low refractive index material. The shift in the defect mode and photonic band gap at the central wavelength 1550 nm with incidence angle, mode of polarization and number of layers in optical communication region is investigated.

Keywords- Photonic crystals, Transfer matrix method, Defect mode, Mode of polarization photonic band gap.

1 Introduction

The L. Rayleigh [1] and Yablonovitch [2] are pioneers for the photonic crystal field. L. Rayleigh in 1887 studies the one dimensional (1D) periodic structure and reports the possibility of totally reflected regions for light with varying incident angle [1]. After that this invention builds up as photonic crystals (PCs). Photonic crystal is artificial micro and nanostructure with spatial periodicity of different refractive index and permittivity of constituent materials. The spatial periodicity of PCs is order of the wavelength of the incident light. They have specific Photonic Band Gap (PBG) property. A certain range of optical wavelengths/frequencies where the existence of light is forbidden within it known as PBG [2]. The attention of researchers in the PCs applications in the field of photonics begins in 1987 [2, 3]. The electrons diffraction in semiconductors and photons diffraction in PCs are similar and due to this analogy PBG property arises[4].If the refractive index or dielectric permittivity periodicity in 1D , the device is known as one dimensional photonic crystal (1D PC), if periodicity in 2D or 3D the device is known as 2D or 3D PC[5]. The 1D PC has imaging PBG property. 1D PC's are frequently used due to its low cost and various applications in linear and nonlinear optical fields [6].

The wavelength in the forbidden band gap observed due to the isolated defect in the periodic structures and the localized electromagnetic wave have been still open area because their applications in optical communication devices. The compounded PCs theme is depends upon the possibility of formation of localized modes in the photonic band gap when a defect is inserted in the lattice [7, 8]. These structures with defects are called as the compounded PCs. Because of the change of the behaviors as a result of the attempt of entry of the incoming waves, it leads to the resonant transmittance peaks in PBG corresponding to the formation of localized conditions. The defect can be created by changing the thickness of the layer in PCs, the refractive index or by removing one of the layers. The optical applications are as microcavity, waveguide and perfect mirror have been used extensively used in 2D and 3D PCs. The localized modes can be created within PBG in ID PCs which can be used as optic devices especially in the fabrication of the narrow band filters and sensors.

In this paper, we theoretically studied the defect mode transmittance characteristics for transverse electric and magnetic mode (TE, TM) at 1550 mm optical transmission frequency in IR region for ID PC for variable incidence angle and number of layers. The effect of variation of incident light angle over position of the defect mode and the resonant peak value were analyzed by using the transfer matrix method (TMM) [9, 10]. Our study can be employed in the optical communications, many applications operating in the infrared optical transmission region such as filters and sensors.

2 Theoretical investigations

The schematic of defective one dimensional Photonic crystal (1D PC) is represented in Figure 1.

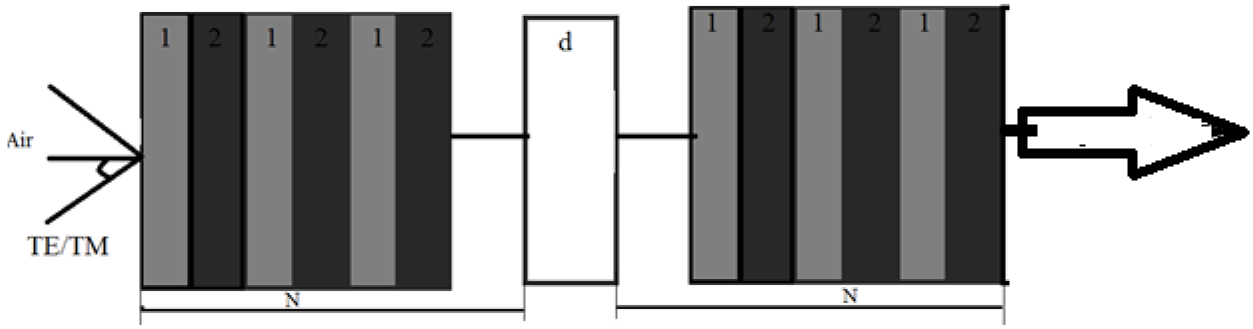


Figure1:-Defective one dimensional Photonic crystal[Air($GaAs/BaF_2$)^N(BaF_2)($GaAs/BaF_2$)^{N}Air].

The defective 1D PCs is considered as the form [Air($GaAs/BaF_2$)^N(BaF_2)($GaAs/BaF_2$)^{N}Air] where N is the number of periods. The device is formed as Gallium arsenide high refractive index material n_1 and barium fluoride low refractive index material n_2 respectively with d_1 and d_2 as the thickness of the layers as per quarter wave stack. The defect layer in the defective 1D PC is barium fluoride with larger thickness (quarter wave stack). Here air is act as the incident and transmission medium.

The transmittance of the proposed device is theoretically calculated using the TMM method [9– 10]. The total matrix for the proposed device is defined as:-

$$M = (M_j)^N = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \quad (1)$$

Thus, the total matrix for the proposed device defective 1D PC is given as:-

$$M = (M_1 M_2)^5 M_d (M_1 M_2)^5 \quad (2)$$

The transmission coefficient is given by:-

$$t = \frac{2p_s}{(m_{11} + m_{12}p_0)p_s + (m_{21} + m_{22}p_0)} \quad (3)$$

Therefore, the transmittance of the proposed device is as follows-

$$T = \frac{p_0}{p_s} |t|^2 \quad (4)$$

3 Results and discussions

Consider the 1D PC structure sequence as [Air($GaAs/BaF_2$)^N(BaF_2)($GaAs/BaF_2$)^{N}Air] in fig 1 and using TMM eq. 4 for calculations. Here N is number of layers and air as incident and transmitted region. The device is formed as Gallium arsenide high refractive index material n_1 and barium fluoride low refractive index material n_2 respectively with d_1 and d_2 as the thickness of the layers as per quarter wave stack. The defect layer in the defective 1D PC is barium fluoride with larger thickness (quarter wave stack).

The simplest periodic medium is one made up of alternating layers of transparent dielectric materials with different refractive indices, n_1 and n_2 . Here it is assumed, that alternating layers have thicknesses, d_1 and d_2. The central wavelength is λ_c. The structure is known as a quarter wave dielectric stack, which means that the optical thickness are quarter-wavelentgh long is

$$n_1 . d_1 = n_2 . d_2 = \frac{\lambda_c}{4} \quad (5)$$

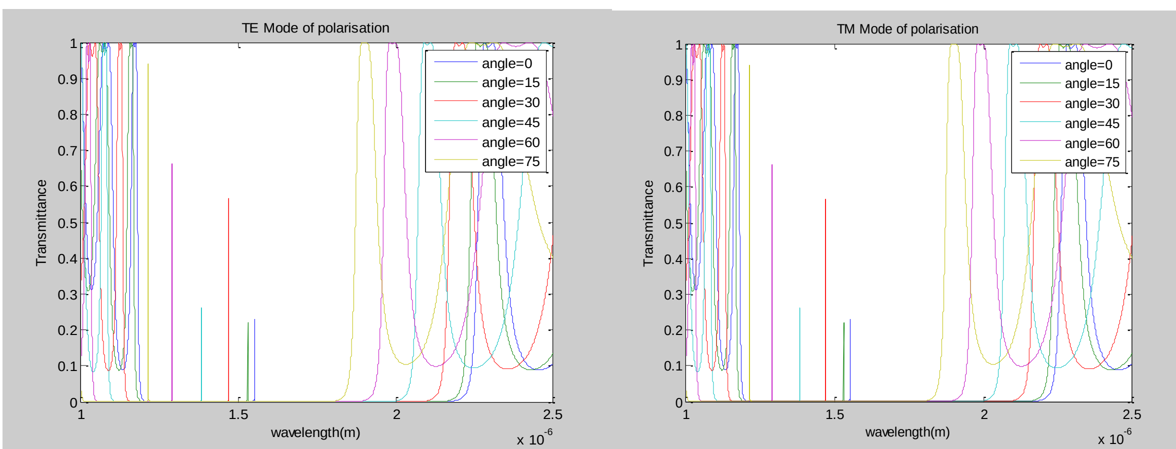
The thickness of defect layer is given by

$$d_d = \frac{\lambda_c}{4n_1} \quad (6)$$

Here λ_c is central wavelength which is the mid wavelength of the spectrum and incident wavelength in the infrared region (IR) considered. The materials GaAs and BaF_2 refractive index are 3.3702 and 1.3705 respectively at wavelength 1550 nm [11, 12]. The refractive index of both materials is considered as constant. The regions in the device are taken linear, lossless, homogenize and nonmagnetic. The layer thickness are $d_1 = 114.98\, nm$ and $d_2 = 282.74\, nm$ respectively considered as quarter wave condition with 1550 nm central wavelength. The defect layer is chosen BaF_2 and its thickness is as eq. 6.

The effects of the defect layer on the transmittance spectrum has been shown at the different angle of incidence for TE and TM mode of polarization with varying number of layers in Fig. 2,3. There is a reduction in the amplitude of the defect peak when the number of layers increases with the varying angle of incidence and mode of polarization. The lower amplitude of peak is due to incomplete resonance. The effect is also on the PBG and the defect peak. The defect peak is shifted towards lower wavelength with increasing the angle of incidence. There is broadening observed in the PBG with increasing angle of incidence.

Number of layers N=5



Number of layers N=4

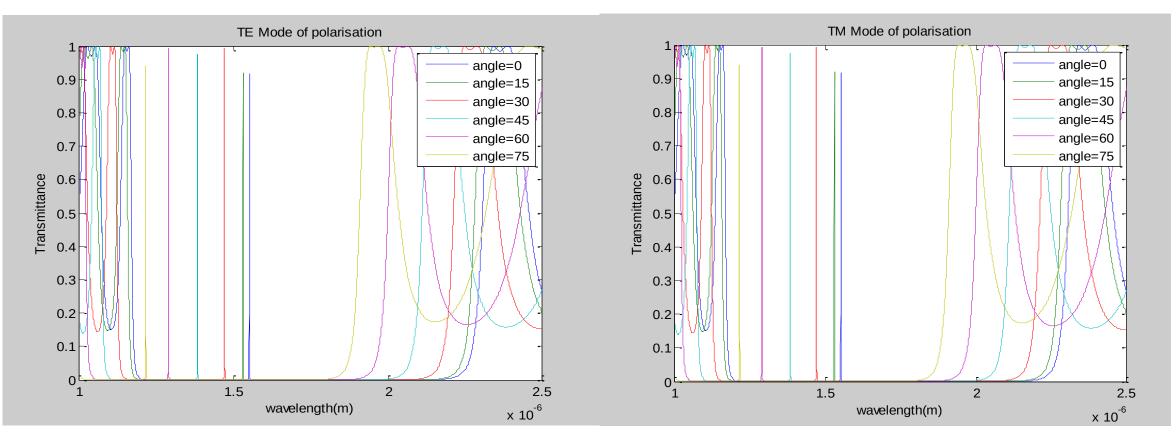
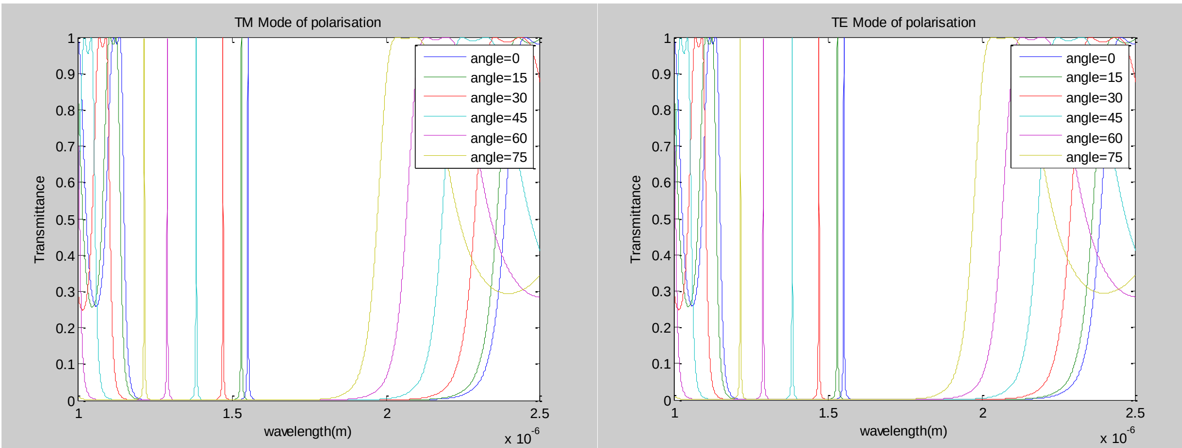


Figure 2- Influence of Polarisation mode and angle of incidence for different number of layers on the defective 1D PC

Number of layers N=3



Number of layers N=2

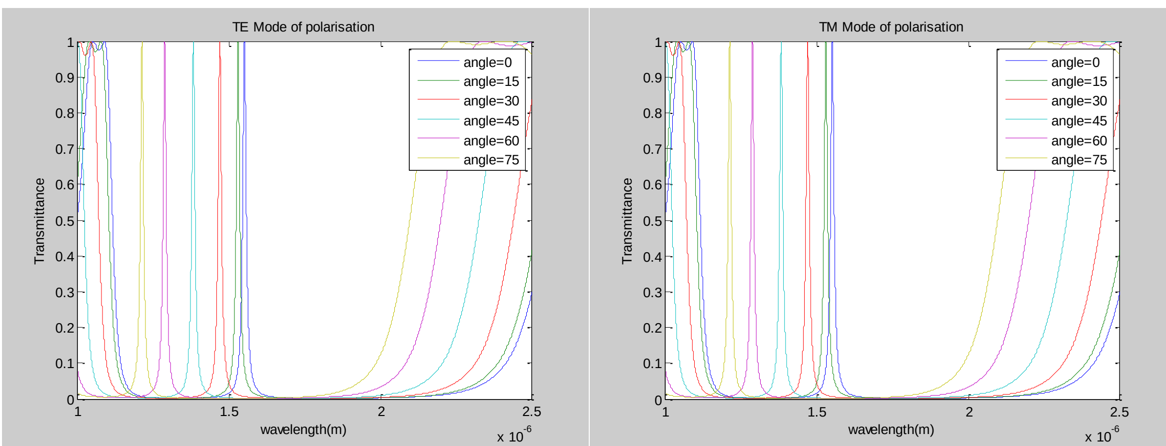


Figure 3- Influence of Polarisation mode and angle of incidence for different number of layers on the defective 1D PC

The conclusion we can draw from fig 2,3 that the proposed device is best for N=2 but it can be used for N= 3 and N=4 , because the depreciation in amplitude is limited. But it cannot be used for N=5 because the decrease in peak amplitude is considerable.

4 Conclusions

In this paper, we investigated transmittance characteristics of electromagnetic wave and photonic band features of 1D PC defect structure using TMM method. A defect is inserted for the central wavelength 1550 nm. The effect of the number of layers, angle of incidence and polarization wave mode are investigated on the position of the defect peak and its amplitude. There is a reduction in the amplitude of the defect peak when the number of layers increases with the varying angle of incidence and mode of polarization. The lower amplitude of peak is due to incomplete resonance. The effect is also on the PBG and the defect peak. The defect peak is shifted towards lower wavelength with increasing the angle of incidence. There is broadening observed in the PBG with increasing angle of incidence. The conclusion we can draw that the proposed device is best for N=2 but it can be used for N= 3 and N=4 , because the depreciation in amplitude is limited. But it cannot be used for N=5 because the decrease in peak amplitude is considerable. The design we have studies is easily fabricated and cheaper than 2D and 3D PC structures. This device can be used in optical communication as filters, sensors and signal multiplexing and demultplexing.

References:-

[1] L. Rayleigh, On the maintenance of vibrations by forces of double frequency, and on the propagation of waves through a medium endowed with a periodic structure, Lond. Edinb. Dublin Philos. Mag. J. Sci., 24 (147), (1887), 145 – 159.

[2] E. Yablonovitch, Inhibited spontaneous emission in solid-state physics and electronics, Phys. Rev. Lett., 58, (1987), 3059 – 3062.

[3] S. John, Strong localization of photons in certain disordered dielectric superlattices, Phys. Rev. Lett., 58, (1987), 2486–2489.

[4] A. Kavokin, J. Baumberg, G. Malpuech, F. Laussy, Microcavities, (Vol. 21), Oxford University Press, 2017.

[5] Lyubchanskii, I.L., Dadoenkova, N.N., Zabolotin, A.E., Lee, Y.P., Rasing, T., A one-dimensional photonic crystal with a superconducting defect layer. J. Opt. A, Pure Appl. Opt. 11, 114014 ,2009.

[6] Aly, A.H.: The transmittance of two types of one-dimensional periodic structures. Mater. Chem. Phys. 115, 391–394 ,2009.

[7] M. Born and E. Wolf, Principle of Optics, 41h edition, Pergamon, Oxford 1, 1970.

[8] F. Fedele, J. Yang and Z. Chen, "Properties of defect modes in onedimensional optically induced photonic lattices," Studies in Applied Mathematics, vol. 115, pp. 279-301,2005.

[9] P. Yeh, Optical Waves in Layered Media, Wiley-Interscience, 2005.

[10] S. Orfanidis, Electromagnetic Waves and Antennas, NJ Rutgers University, New Brunswick, 2002.

[11] T. Sakuli et. al., "Improved dispersion relations for GaAs and applications to nonlinear optics"Journal of Applied Physics, **94**, 6447 ,2003.

[12] Marilyn J. Dodge, Refractive properties of magnesium fluoride, Applied optics , Vol. 23, No. 12 ,1984.